Investigation of Mass Flows Beneath a Sunspot by Time-Distance Helioseismology

Junwei Zhao and Alexander G. Kosovichev
W. W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA94305-4085
and

Thomas L. Duvall Jr.
Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771

ABSTRACT

A time-distance helioseismic technique is employed to analyze a set of high-resolution Dopplergram observations of a large sunspot by SOHO/MDI on June 18, 1998. A regularized damped least-squares inversion is applied to the measurements of travel times to infer mass flows around the sunspot below the solar surface. Powerful converging and downward directed flows are detected at a depth of 1.5 to 5 Mm, which may provide observational evidence for downdrafts and vortex flows suggested for a cluster model of sunspots by Parker. Strong outflows which extends more than 30 Mm are found below the downward and converging flows. It is suggested that the sunspot might be a relatively shallow phenomenon with a depth of 5-6 Mm as defined by its thermal and hydrodynamical properties. A strong mass flow across the sunspot is found at depth of 9–12 Mm, which may provide another evidence in support of the cluster model as oppose to the monolithic sunspot model. A new magnetic emergence found 5 hours after our analysis period is suggested to be related with this mass flow.

Subject headings: Sun: helioseismology — Sun: sunspots — Methods: data analysis

1. Introduction

How material flows around a sunspot is an interesting topic that has been studied for decades. Measurements of the subsurface flow could help us to understand how the sunspots form, grow, evolve and decay. The Evershed effect is a well-known phenomenon, which is observed as a prominent outflow from the inner sunspot penumbra to its surrounding photosphere (Evershed 1909). With the development of new technology to achieve better spatial and temporal resolution, more details of the Evershed effect have been disclosed. Recent results show that Evershed outflows concentrate mainly in narrow and elongated radial penumbral channels (Rimmele 1995; Stanchfield et al. 1997). This suggests that the Evershed effect is only a superficial phenomenon at the solar surface. More recent studies of vertical flows have found hot upflows in the inner penumbra, which feed the horizontal Evershed flow, and cool downflows surrounding the outer penumbra where the horizontal Evershed flow terminates (Schlichenmaier and Schmidt 1999).

The studies mentioned above are conducted by direct spectral observations, which cannot determine how material flows beneath the surface. Time-distance helioseismology pioneered by Duvall et al. (1993) provides a very useful technique to probe the interior structure and mass flows beneath the solar surface. Using the time-distance technique based on travel time measurements of solar surface waves (f mode), Gizon et al. (2000) detected a radial outflow, which has an average velocity of about 1 km s^{-1} in the top 2 Mm below the photosphere, extended from sunspot center up to 30 Mm outside the sunspot umbra. Since the inferred outflow is significantly smaller than the surface outflow speed measured by Doppler velocity, they suggested the Evershed flow is very shallow, which is consistent with conclusions from direct spectral observations. Because of the surface nature of the f mode, these results can only reflect horizontal material motions in shallow layers just beneath the surface (Duvall and Gizon 2000).

The origin of sunspots is not understood. Parker (1979) suggested a cluster model for sunspots. In order to hold together the loose cluster of magnetic flux tubes, a downdraft beneath the sunspot in the convection zone is needed. But so far, this model lacks direct observational evidence. Though Duvall et al. (1996) have obtained evidence for downflows under the sunspot by use of the time-distance technique, some authors (e.g., Woodard 1997; Lindsey et al. 1996) put this conclusion in suspicion.

In this paper, we apply the time-distance technique based on measuring travel times of acoustic waves (p modes) to one set of continuous Dopplergram observations by SOHO/MDI. These travel times are inverted to probe the plasma flows under and around the sunspot region. The clear flow picture deep below and around the sunspot presented in this paper provides strong support to the cluster sunspot model and emergence of magnetic Ω loops.

2. Observations and Time-Distance Data Analysis

The one set of data analyzed are high resolution Dopplergrams with one-minute cadence, obtained from the Michelson Doppler Imager (MDI) aboard SOHO (Scherrer et al. 1996). The observations began at 15:37UT of June 18, 1998, and lasted for approximately 13 hours. A sunspot was at the center of the field of view and remained stable during the observation period. The resolution of observation is 0.032°/pixel, and after a 2×2 rebin, we get an image of 256×256 pixels with resolution of 0.068°/pixel for each one-minute cadence. (Here, 1° represents 1 heliographic degree, which is approximately 12.15 Mm.)

Solar acoustic waves (p modes) are excited in the convection zone and travel to the surface through the interior. The travel time of an acoustic wave packet depends primarily on the sound speed and on the velocities of mass flows along its propagation path. In the time-distance technique we measure the acoustic waves travel times from a point at the solar surface to annuli around this point, along curved ray paths which go through into the interior. The measurements are obtained by fitting the cross-covariance function between Doppler velocity time series at the central point and the average velocity series of all the points in the annuli. Despite the turbulent noise on the solar surface and stochastic nature of sound waves, this technique can give convincing results of travel time after filtering out noise, low-frequency waves (which are believed unreliable) and applying a phase-speed filtering (Duvall et al. 1997; Giles 1999). The travel times are used to infer information about mass flows and other inhomogeneities along the wave travel paths by inversion.

In order to get information about the deep interior rather than shallow surface layers, we filter out surface gravity waves (f mode), and analyze signals from acoustic waves (p modes). Flow velocities are calculated from the travel time differences of outgoing waves (from the central point to its surrounding annuli) and ingoing waves (from the surrounding annuli to the central point). We denote this time difference as $\delta\tau^{oi}$. In addition, we divide the annuli into four quadrants corresponding to four directions of East, West, South and North. After computing the cross-covariance functions of signals from these four quadrants with those from the central point, the travel time difference of waves from West to East with waves from East to West, denoted as $\delta\tau^{we}$ are obtained. Similarly, the travel time difference in North-South directions can be calculated and denoted as $\delta\tau^{ns}$. More detailed descriptions of this method are presented by Duvall et al. (1997) and Kosovichev and Duvall (1997).

We applied this technique to every point in the MDI high-resolution Dopplergrams, and chose ten different ranges of annulus distances: 0.30–0.71, 0.51–0.92, 0.71–1.20, 1.20–1.60, 1.60–2.41, 2.14–2.89, 2.62–3.43, 3.16–3.91, 3.64–4.45 and 4.18–4.93 heliographic degrees, measuring travel time for each of these distances. To account for variations of the differential rotation with depth we subtracted from our travel-time differences the corresponding mean values of the differences for a quiet Sun region.

3. Inversion

3.1. Experiments on Inversion Code

Kosovichev (1996) applied an inversion technique used in geophysical seismic tomography to develop a new way to detect the mass flows and other inhomogeneities (e.g. sound speed variation) beneath the visible surface of the Sun. Detailed description of the method can be found in that paper. Equations relating flowing speed and travel time differences were solved by a regularized damped least-square technique (Paige and Saunders 1982).

In order to check the spatial resolution of our calculation code, we designed some artificial data to simulate the flows in the solar interior. The travel time differences are calculated as a forward approach, then the inversion was done to get the flow speeds. We found that, generally, the flows in the upper layers can always be recovered well, but flows in the lowest layers may be smaller than the input values (see also Kosovichev and Duvall 1997). We also found that in some specific cases, because of a cross-talk between horizontal flows and vertical components of flow velocities, it may be impossible to recover the original data. But, for localized strong flows such as in sunspots, the cross-talk effects do not occur. Figure 1 shows a calculation result from a set of our artificial data which has relatively strong motions in the central region. It can be found that the flow pattern are recovered well, but the velocity magnitude in the lower layers is somewhat smaller than the input. Therefore, the inferred mass flow speeds in the upper layers of the sunspot region should be quite credible. In the lower layers these speeds are underestimated.

To double check our inversion results, we compute the travel time differences as a forward approach from the velocities inferred from the inversion, which are compared with the travel time differences computed from time-distance analysis. These travel time differences were used to compute the flow velocities by inversion again to compare with the previous results. Good agreements were achieved from our calculations in both procedures. That means the observational data are sufficient for recovering both the horizontal and vertical components of the velocities in the investigated sunspot region.

3.2. Inversion Results

We average the calculated travel time differences in 2×2 pixel bins, thus obtain 128×128 bin maps for each $\delta\tau_{oi}, \delta\tau_{we}$ and $\delta\tau_{ns}$ for the 10 different annulus ranges described in Section 2. We adopt a ten-layer discrete model in depth of the sunspot region, and use the same number of pixels in each layer as in the time-distance measurements. The depth ranges for 10 layers are: 0–3, 3–4.5, 4.5–6, 6–9, 9–12, 12–14, 14–16, 16–18, 18–20.5 and 20.5–23 Mm. The results are presented in Figure 2 and Figure 3.

Figure 2 shows the mass flows in the first and the fourth layers, with arrows showing the direction and strength of the horizontal flows, and the background image showing the vertical velocities. From Fig. 2a which shows results for the first layer corresponding to an average of depth of 0–3 Mm, we can clearly identify a ring of strong downflows around the sunspot, with relatively weaker downflows inside the ring. Converging flows at the sunspot center can also be seen in this graph. Fig. 2b shows the flows in the fourth layer, corresponding to a depth of 6–9 Mm. The sunspot region is occupied by a ring of upflows with relatively smaller downward velocity at the center. Outside this region, the results are a little noisier, but downward velocities seem dominant in the region immediately outside the sunspot. Strong outflows from the sunspot center can be seen, extending more than 30 Mm from the sunspot center. Fig. 2c is the flows in the fifth layer, average of depth of 9–12 Mm, where powerful upflows occupy the whole sunspot region. It is of more interests to notice the horizontal mass flows in this layer. Some materials from the West flow right across the sunspot region, and continue moving mainly to the South-East quarter of the graph.

Figure 3 shows two vertical cut graphs, one with East-West direction, the other North-South direction, through the center of the sunspot. Although the ten layers were calculated from observation, we only use the upper eight layers to provide more reliability to the results according to our test inversions. The velocities from inversion are actually the average velocities in the block. We assume these as the velocities at the center of the block, and also assume the velocities change uniformly from the block to its neighboring blocks, and calculate the speeds in between two layers by use of linear interpolation. Converging and downward flows can be seen in both graphs right below the sunspot region from 1.5 Mm to about 5 Mm. Below that, the horizontal outflows seem to dominate in this region, though relatively weaker upflows also appear. Below a depth of $\sim$10 Mm, the flows seem not to be concentrated in the region vertically below the sunspot. This can be seen more clearly in the East-West cut. It is intriguing that an upflow toward East dominates in the region from 10 Mm to 18 Mm. In South-North cut graph, this pattern is not so clear but still can be seen, with the upflow toward South direction stronger than toward the North.

In order to check whether the velocity distribution can keep the structure stable or quasi-steady, $\nabla \cdot (\rho \mathbf{v})/\rho$ was computed, where ρ is the density from a standard solar model. The largest value is at the order of 10^{-4} s^{-1}, slightly larger than the inverse of duration of observation. However, the density distribution inside the sunspot and around it, where magnetic field should be significantly large and temperature obviously low, is probably significantly different from the standard model, and remains to be determined. Therefore, it is quite possible that the velocity distribution shown in the graph is consistent with the sunspot structure.

It is of great interest to determine a characteristic of kinetic helicity of the inferred flows, which might have implications for magnetic field generations and solar activity cycle. Using the inferred velocities, $\alpha \equiv \mathbf{v} \cdot (\nabla \times \mathbf{v})/\mathbf{v}^2$ was calculated. In and near the sunspot region, α is close to 0, both positively and negatively. It is hard to tell which sign is dominant from the noise. Higher resolution observations may be possible to find the relationship between helicity and the flux distribution in the convection zone.

4. Discussion

We have presented our best estimates of flows associated with a sunspot, and believe that these provide an accurate qualitative description of the flow pattern. Several factors could affect the accuracy of our results. It is unavoidable to have averaging effects between neighboring pixels and neighboring layers in our calculations. So, the flow speeds shown in Figures 2 and 3 can not represent the exact magnitudes, directions or locations, but some average values with their neighboring pixels and layers. Also, we have to bear in mind that the flows shown in Figures 2 and 3 are averages of 13 hours of observation. That means our inferences can only reflect flow patterns stable for a long time run rather than instantaneous speed at any observation time.

In our calculation, we assume that the travel time differences from time-distance analysis are totally due to mass flows, and we employ the geometrical ray approximation. Woodard (1997) and Birch and Kosovichev (2000) argued that some other factors, such as non-uniform distributions of acoustic sources and finite wavelength effects, may also affect travel times, which may greatly complicate our analysis, in particular, quantitative inferences.

In both graphs of Figure 3, powerful converging and downward flows are found from 1.5 Mm to $\sim$5 Mm beneath the surface. Meyer et al. (1974) predicted the existence of the converging flow ($\sim$1 km/s at a depth of several Mm) as a collar around the sunspot to provide the confinement and stability of sunspots. The material downdrafts below the sunspot were also required to keep the cluster of magnetic fluxes confined under the sunspot in the cluster sunspot model (Parker 1979). Our observation seems to have provided strong evidence for both predictions. More recent numerical simulations (Hurlburt and Rucklidge 2000) show in more detail the converging and downward flows below the sunspot surface, and the upflow near the moat, which are in good agreement with our observation not only in converging and downward flows, but also in upflows near the moat (a little weaker in our results than the simulation). The converging and downward flow beneath the sunspot cannot be immediately consistent with the other observing facts of upward and diverging flows at the surface, as described in Section I. Further studies of the shallow region from the surface to a depth of 2 Mm should be done more carefully including the f mode data (Gizon et al. 2000).

Besides the cluster model, monolithic model is another widely proposed sunspot model. It suggests the sunspot is one large magnetic flux tube below the photosphere rather than dividing into some small flux tubes. If this is true, one should expect no materials can flow across the monolithic magnetic tube. But our results in Fig 2c shows the otherwise. This may be another evidence to support the cluster model, which does not prohibit the mass flow across the lower part of a sunspot.

It is clear that magnetic inhibition of convection is most effective within 1.5 Mm of the photosphere (Thomas and Weiss 1992). The temperature difference, ΔT, between the sunspot umbra and the mean undisturbed atmosphere at the level of the Wilson depression is about 9000K, but ΔT decreases rapidly with depth. The estimated value of ΔT falls to 500K at depth of 2 Mm, and then to 25K at depth of 6 Mm (Meyer et al. 1974). The sunspot would be a shallow phenomenon if it were defined by its thermal properties alone. Our calculation of flows shows that converging and downward flows disappear below the depth of $\sim$5 Mm, which is an approximate depth where ΔT vanishes. So, it may be interpreted that, the converging and downward flows beneath the sunspot are phenomena related to the sunspot's thermal properties. These flows disappear as the temperature difference of the sunspot with its surroundings vanishes.

It is widely believed that a sunspot is formed when the magnetic Ω loop rises from the deeper convection zone and emerges at the solar surface. The sunspot is located where the Ω loop emerges and where strong magnetic flux bundles concentrate. The flux bundles will stop rising after the sunspot reaches its maximum, but plenty of other magnetic flux keeps rising from the convection zone at the local site (Parker 1994). There must be plenty of magnetic flux tubes which are underlying the sunspot but do not emerge on the surface despite of magnetic buoyancy. Fig. 2c shows a strong mass flow across the sunpot, if some magnetic flux tubes underlying the spot are blown away to the South-East of the sunspot, and brought up by some upflows (some strong upflows can be found at the lower left corner of Fig. 2c), magnetic emergence at the surface will be expected after $\sim$4 hours (from a depth of 9–12 Mm, the rising speed is around 0.7 km/s). We checked MDI full-disk magnetograms, and found about 5 hours after our analysis period, at 09:40UT of June 19, a magnetic emergence was first seen at the exact site of the upflows seen in Fig. 2c. The pores with opposite polarities developed into their maxima after 12 hours. Figure 4 shows the magnetogram before the magnetic emergence and after it reaches the maximum. The sound-speed perturbation analysis of the same sunspot by Kosovichev et al. (2000) revealed that the sunspot is connected with the pore of same polarity in the deep interior, which may confirm our assumption that these two newly emerged pores were formed by rising Ω loops which might have broken away from the main magnetic flux bundles. We have also noticed another fact that the proper motion of this sunspot during the observation is toward the direction South-East. It may be caused by the South-East directed motion of lower portion of the sunspot seen in Fig 2c due to an unknown reason. Obviously, more high-resolution helioseismic observations are required to confirm these results. Such observations could offer a unique opportunity for solving one of the great puzzles of astrophysics – the origin of sunspots.

REFERENCES

Birch, A. C. and Kosovichev, A. G. 2000, Sol. Phys., 192, 193

Duvall Jr., T. L., Jefferies, S., M., Harvey, J. W. and Pomerantz, M. A. 1993, Nature, 362, 430

Duvall Jr., T. L., D'Silva, S., Jefferies, S. M., Harvey, J. W. and Schou, J. 1996, Nature, 379, 235

Duvall Jr., T. L., et al. 1997, Sol. Phys., 170, 63

Duvall Jr., T. L. and Gizon, L. 2000, Sol. Phys., 192, 177

Evershed, J. 1909, MNRAS, 69, 454

Giles, P. M. 1999, Ph. D. Thesis, *'Time-Distance Measurements of Large-Scale Flows in the Solar Convection Zone'*, Stanford University

Gizon, L., Duvall Jr., T. L. and Larsen, R. M. 2000, J. of Astrophy. Astr., in press

Hurlburt, N. E. and Rucklidge, A. M. 2000, MNRAS, 314, 793

Kosovichev, A. G. 1996, ApJ, 461, L55

Kosovichev, A. G. and Duvall Jr., T. L. 1997, in J. Christensen-Dalsgaard & F. Pijpers (eds), 'Solar Convection and Oscillations and their Relationship', *Proc. SCORe'96 Workshop*, Aarhus, May 27-31, 1996, Kluwer, Dordrecht, 241

Kosovichev, A. G., Duvall Jr., T. L. and Scherrer, P. H. 2000, Sol. Phys., 192, 159

Lindsey, C., Braun, D. C., Jefferies, S. M., Woodard, M. J., Fan, Y., Gu, Y., and Redfield, S. 1996, ApJ, 470, 636

Meyer, F., Schmidt, H. U., Weiss, N. O. and Wilson, P. R. 1974, MNRAS, 169, 35

Paige, C. C. and Saunders, M. A. 1982 ACM Trans. Math. Software, 8, 43

Parker, E. N. 1979, ApJ, 230, 905

Parker, E. N. 1994, ApJ, 433, 867

Rimmele, T. 1995, A&A, 298, 260

Scherrer, P. H., et al. 1996, Sol. Phys., 162, 129

Schlichenmaier, R. and Schmidt, W. 1999, A&A, 349, L37

Stanchfield II, D. C. H., Thomas, J. H. and Lites, B. W. 1997, ApJ, 477, 485

Thomas, J. H. and Weiss, N. O. 1992, in J. H. Thomas and N. O. Weiss(eds.), 'Sunspots: Theory and Observations', 1992, Kluwer Academic Publishers, Netherlands, 3

Woodard, M. F. 1997 ApJ, 485, 890

This 2-column preprint was prepared with the AAS LaTeX macros v5.0.

Fig. 1.— The experiment on our calculation code. The upper graph shows artificial data which simulates stronger speeds at the center than other regions. The lower graph shows the inversion results.

Fig. 2.— The material flows in the depth of 0–3 Mm (a), depth of 6–9 Mm (b) and depth of 9–12Mm (c). The arrows show the magnitude and directions of the horizontal flows, and the background shows the vertical flows. Positive indicates downflow. The contours at the center are corresponding to umbra and penumbra boundaries. The longest arrow represents 1.0 km/s for (a), and 1.6 km/s for (b) and (c). The arrows outside frame indicate where the cut is made to obtain graphs in Fig. 3.

Fig. 3.— Vertical cuts through the sunspot center with the cut direction of East-West (*upper*, with East on the left side) and South-North (*lower*, with South on the left side). The range covered by the line arrows indicate the area of umbra, and the range covered by the dotted arrow indicate the area of penumbra. The longest arrow represents 1.4 km/s.

Fig. 4.— The magnetograms taken by SOHO/MDI at 04:30UT (*left*) and 22:00UT (*right*) on June 19, 1998.